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EFFECT OF THE RADIANT COMPONENT ON HEAT TRANSFER IN VACUUM SUBLIMATION

P. A. Novikov

When various substances are sublimated in vacuum apparatus, radiant heat transfer is mainly confined to the inner surface of the sublimator, with temperature T_w, and the surface of the material sublimated, with temperature T_{sm}. In heat transfer processes the radiant component depends both on the absolute values of the temperatures T_w and T_{sm} and on the quality and state of the radiation and absorption surfaces, which are characterized by the emissivity and absorptivity, or the degree of blackness of the bodies involved in the radiative heat exchange. If the wall temperature of the vacuum chamber is constant, the temperature of the sublimated surface will vary with both the thermodynamic and the hydrodynamic parameters of the ambient medium. On sublimation under free-convection conditions with a reduction in the total pressure, the temperature of the surface of the material falls, whereas under conditions of forced convection, when the pressure and the temperature of the ambient medium are constant, the fall in the temperature of the material depends on the rate of motion of the body or the medium. A dependence of the surface temperature of the body on the rate of motion is observed only in the region of viscous behavior. Under molecular-viscous conditions, when slip and temperature-jump effects begin to appear near the sublimating surface, i.e., at Knudsen numbers of more than 0.04, the surface temperature of the body is practically independent of the rate of motion (range investigated: from 0 to 50 $m \cdot sec^{-1}$).

The specific radiant heat flux can be determined starting from the Stefan-Boltzmann law for the case of radiative heat

transfer between bodies, one of which is contained inside the other, namely:

$$q_r = C_{red}\left[\left(\frac{T_W}{100}\right)^4 - \left(\frac{T_{sm}}{100}\right)^4\right] \quad (\text{kcal}\cdot\text{m}^{-2}\cdot\text{hours}^{-1}),$$

$$C_{red} = \frac{1}{\frac{1}{C_1} + \left(\frac{1}{C_2} - \frac{1}{C_s}\right)\frac{F_1}{F_2}} \quad (\text{kcal}\cdot\text{m}^{-2}\cdot\text{hours}^{-1}\cdot{}^{o}\text{K}^{-4}).$$

It follows from the equation that if the temperature of the walls of the vacuum chamber is constant, the variable parameters will be the surface temperature of the material and its degree of blackness. It is very difficult to make an accurate determination of the degree of blackness of certain materials (ice and other substances containing moisture) during the process of vacuum sublimation, since during sublimation the surface of the material changes its properties, which, obviously, has an effect on the degree of blackness. Thus, in the case of vacuum sublimation it is not always possible to separate the radiant component with any accuracy.

The object of the present paper is to determine the effect of the radiant component of the total heat balance on the nature of the heat and mass transfer for a constant temperature of the vacuum chamber walls and variable pressure of the ambient medium. The experiments on the sublimation of a naphthalene sphere at different pressures of the ambient medium show (see Table) that the specific radiant heat flux increases monotonically with decrease in the total pressure whereas the total heat flux varies with the pressure in accordance with a more complicated law. As for the contribution of the radiant component to the total heat transfer, it assumes different values as the pressure varies.

TABLE

Specific Radiant Heat Flux as a Function of the Temperature of the Sublimated Surface of a Naphthalene Sphere under Vacuum Conditions.

P mm Hg	w, $m \cdot sec^{-1}$	q_o, $kcal \cdot m^{-2} \cdot hours^{-1}$	q_r, $kcal \cdot m^{-2} \cdot hours^{-1}$	t_w, oC	t_{sm}, oC	α_r $kcal \cdot m^{-2} \cdot hours^{-1} \cdot {}^oC^{-1}$
742	0.0	1	0.4	20.8	20.6	2
500	0	1.25	0.6	20.8	20.5	2
300	0	1.43	0.8	20.8	20.4	2
100	0	2.5	1.6	20.8	20	2
100	10	11.25	4.4	20.8	18.6	2
100	20	15.6	4.6	20.8	18.5	2
100	30	20	4.8	20.8	18.6	2
100	40	24.4	5	20.8	18.3	2
100	50	28.8	5.2	20.8	18.2	2
40	0	5	3.6	20.4	18.6	2
40	10	20	5.2	20.4	17.8	3
40	20	26.9	5.6	20.4	17.6	2
30	30	33.7	5.9	20.4	17.4	2

[Table continued]

P mm Hg	w, $m \cdot sec^{-1}$	q_o, $kcal \cdot m^{-2} \cdot hours^{-1}$	q_r, $kcal \cdot m^{-2} \cdot hours^{-1}$	t_w, °C	t_{sm}, °C	α_r $kcal \cdot m^{-2} \cdot hours^{-1} \cdot °C^{-1}$
30	40	40.05	6.3	20.4	17.2	2
30	50	47.5	6.7	20.4	17	2
4	0	31.3	9.2	20.2	15.5	1.95
4	10	65	11.2	20.2	14.5	1.95
4	20	78	11.9	20.2	14.1	1.95
4	30	87.5	12.3	20.2	13.9	1.95
4	40	95.5	12.7	20.2	13.7	1.95
4	50	103	13.1	20.2	13.5	1.95
1	0	58.78	15.6	19.5	11.4	1.93
1	10	97	16.7	19.5	9.6	1.68
1	20	109	18.1	19.5	9	1.72
1	30	116	19.6	19.5	8.8	1.83
1	40	122.5	20.3	19.5	8.6	1.86

[Table continued]

P mm Hg	w, $m \cdot sec^{-1}$	q_o, $kcal \cdot m^{-2} \cdot hours^{-1}$	q_r, $kcal \cdot m^{-2} \cdot hours^{-1}$	t_w, ^oC	t_{sm}, ^oC	α_r $kcal \cdot m^{-2} \cdot hours^{-1} \cdot {}^oC^{-1}$
1	50	125	20.9	19.5	8.5	1.9
0.5	0	71.25	16.6	20	11.4	1.93
0.5	10	95	17.7	20	10.8	1.93
0.5	20	105	19.2	20	10	1.93
0.5	30	111	20.4	20	9.3	1.9
0.5	40	115.5	21.5	20	8.7	1.9
0.5	50	118.5	21.9	20	8.5	1.9
0.27	0	68.75	19.2	20	10	1.92
0.27	10	87.5	21.3	20	8.8	1.92
0.27	20	95.75	21.9	20	8.5	1.92
0.27	30	101	22.6	20	8.1	1.9
0.27	40	104.5	23.1	20	7.8	1.9
0.27	50	107.5	23.5	20	7.6	1.9

[Table continued]

P mm Hg	w, $m \cdot sec^{-1}$	q_o, $kcal \cdot m^{-2} \cdot hours^{-1}$	q_r, $kcal \cdot m^{-2} \cdot hours^{-1}$	t_w, ^oC	t_{sm}, ^oC	α_r $kcal \cdot m^{-2} \cdot hours^{-1} \cdot {^oC}^{-1}$
0.11	0	40.5	22.9	19.2	7	1.88
0.11	10	42.5	23.3	19.2	6.8	1.88
0.11	20	44.5	23.6	19.2	6.6	1.88
0.11	30	46.25	24	19.2	6.4	1.88
0.11	40	48.1	24.3	19.2	6.2	1.88
0.11	50	50	24.7	19.2	6	1.88
0.09	0	43.75	25.1	19	5.5	1.86
0.09	10	43.75	25.1	19	5.5	1.86
0.09	20	43.75	25.1	19	5.5	1.86
0.09	50	43.75	25.1	19	5.5	1.86
0.07	0	53.75	26	19	5	1.86
0.07	10	53.75	26	19	5	1.86
0.07	20	53.75	26	19	5	1.86

Under the conditions of these experiments, the contribution of the radiant heat flux was $\approx$ 30-50 % of the total heat flux. In a number of cases sublimation proceeds when the difference between the temperature of the chamber walls and the temperature of the sublimated surface is only small (period of sublimation with falling drying rate of moist materials). Under these conditions any change in the specific radiant heat flux will be almost proportional to the temperature heat $\Delta T = T_w - T_{sm}$. end If ΔT is small, the fourth-degree equation assumes a simpler form, namely:

$$q_r = \sigma\,(T_w^4 - T_{sm}^4) = \sigma\,[(T_{sm} + \Delta T)^4 - T_{sm}^4] =$$

$$= \sigma\,\Delta T\,(4T_{sm}^3 + 6T_{sm}^2\,\Delta T + 4T_{sm}\,\Delta T^2 + \Delta T^3).$$

For small values of ΔT the expression in parentheses will be negligibly different from $4T_{sm}^3$, and we can then write:

$$q_r = 4\,\sigma\,T_{sm}^3\,\Delta T = 4\,C_{red}\,100^{-4}\,T_{sm}^3\,\Delta T = 0.04C_{red}\left(\frac{T_{sm}}{100}\right)^3\Delta T,$$

where $\alpha_r = 0.04\,C_{red}\,(T_{sm}/100)^3$. From this equation it follows that for a small temperature difference the radiative heat losses can be put in a form analogous to the simplest form of the mathematical description of convective heat transfer, namely:

$$q_r = \alpha_r \Delta T.$$

In our case α_r was determined from the relation $\alpha_r = q_r/\Delta T$, where q_r was calculated from the fourth-power law. The calculations show that for our experiments α_r remains almost constant in the pressure interval between 760 and 0.1 mm Hg and only at pressures of less than 0.1 mm Hg does it differ by as much as 7% from its values at higher pressures. The experiments show that for the cases in question the radiant component has almost no effect on the nature of heat transfer during vacuum sublimation.

NOTATION

C_1 - radiation factor of sublimated material; C_2 - radiation factor of walls of vacuum chamber; $C_s = 4.96$ - radiation factor of absolutely black body; F_1 - surface area of sublimated material; F_2 - inside surface area of vacuum chamber; ϵ_1 - degree of blackness of surface of sublimated material; ϵ_2 - degree of blackness of walls of vacuum chamber; $\sigma = C_{red} 10^{-8}$ - radiation factor; C_{red} - reduced radiation factor.

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